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REVIEW ARTICLE

Advances and trends in weed management: A comprehensive review

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Abstract

Weed management is a critical aspect of agricultural practices that can significantly impact crop yield and quality. As traditional methods face challenges such as herbicide resistance and environmental concerns, the agricultural sector is witnessing a shift towards innovative strategies for weed control. This review explores the emerging trends in weed management, focusing on sustainable and efficient approaches. Among them, one prominent trend is the adoption of agro ecological weed management strategies, which combine various control methods such as cultivation techniques, mechanical techniques, biological control and reasonable herbicide use. This approach minimizes reliance on herbicides while maximizing weed suppression and preserving natural ecosystems. Another significant trend is developing and utilizing precision agriculture technologies for targeted weed control techniques such as satellite imaging, unmanned aerial vehicles (UAVs) and sensor-based systems. These innovations enable farmers to accurately identify and manage weeds, reducing herbicide usage and minimizing environmental impact. Furthermore, the exploration of alternative weed control methods, including thermal, electrical and microwave-based technologies, is gaining momentum. These non-chemical approaches offer potential solutions to herbicide-resistant weeds and contribute to sustainable agricultural practices. Moreover, the integration of advanced breeding techniques and biotechnology for developing herbicide-resistant crops and enhancing allelopathic traits presents promising avenues for long-term weed management. In conclusion, this review highlights emerging technology for dealing with major problems, including increased understanding of weed biology linked with genomics; novel herbicide-resistant crops and redesigned weed-competing crops; multi-target herbicides; and enhanced biocontrol agents. When combined, these strategies could make up the elements of the next integrated packages designed to impede the emergence of new weed issues.

Keywords

agro ecological weed; novel technologies; weed; weed seed bank

Introduction

Meeting the rising demand for food and fiber amidst a shrinking rural workforce, expanding bioenergy needs, fostering agricultural development in developing nations, embracing sustainable practices and adjusting to climate change are key challenges confronting 21st-century agriculture (1). Weeds are generally defined as unwanted or invasive plants that compete with cultivated crops for resources, adversely affecting agricultural productivity and biodiversity. Their presence can lead to substantial yield losses, necessitating effective control strategies. Problematic weeds, such as weedy rice and invasive species increasingly challenge agriculture by impacting crop yield, quality and profitability (2). Conventional weed management techniques, like chemical and mechanical, are sometimes imprecise and can result in environmental problems like chemical runoff and soil erosion and the rise of herbicide-resistant weeds while biological weed management has drawbacks such as high upfront cost, sluggish action and inconsistent efficacy. Therefore, we must move from relying solely on one strategy to an integrated one (3). Globally, there are 530 instances of herbicide-resistant weeds across various species and sites of action. Among these, 272 species (155 dicots, 117 monocots) have developed resistance, affecting 21 of 31 herbicide sites and 168 herbicides. Resistant weeds have been found in 100 crops across 72 countries (4). A holistic, multidisciplinary approach integrating diverse management strategies, including crop genotypes and customized techniques is needed for eradicating this challenge (5). The current overreliance on herbicide-resistant crops is unsustainable, necessitating a shift towards agroecological practices (6). As weed populations continually adapt to emerging selective pressures, a comprehensive understanding of weed biology and ecology is indispensable for implementing effective and enduring management strategies. Therefore, this review aims to provide proper and systematic documentation of different weed management technologies that have been developed to date. This documentation will offer a new perspective for future novel investigations for rectifying faults in current technologies and making more effective technologies (Fig. 1).

Many factors including weeds, insect pests, illnesses, edaphic factors and climate conditions, can lower crop yields. One of the main obstacles to crop yield and production is weeds. Depending on the type of crop, the region and the agroecology (soil type, moisture condition), crop loss from weed infestation varies. Yield reductions due to unchecked weed development ranged from 45 to 73.2% during the agricultural production season. Estimates of the losses for wheat, maize, rice, sorghum and barley range from 26-29%, 31%, 90%, 60% and 64%, respectively (7). Weed competitiveness and suppressive influence on light, nutrients and moisture have led to these losses. Additionally, weeds can serve as different habitats for illnesses and insects, which could have an indirect impact on the crop. Some of the weed management techniques used in major cropping systems are provided in Table 1.

Review methodology

A systematic literature search was performed using Scopus, Google Scholar, Research Gate and SciDirect. The search terminologies included "weed management", "precision weed management technologies", "AI in weed management" and "Omics in weed management" which were used for critical analysis of work being done earlier. A total of 104 relevant works were found. Based on those works, critical analysis has been conducted for the review.

Conventional approaches

Cultural method

Stale seedbed technique: By preparing the seedbed several days, weeks, or months before sowing or planting a crop, stale seedbed techniques aim to flush out germinating weed seeds before crop planting. This process helps in depleting the weed seed bank in the soil surface layer and reduces subsequent weed seedling emergence. It was found that implementing the false seedbed method with shallow tillage at 1-week reduced weed biomass by up to 34% compared to conventional seedbed preparation while forage yield increased by 9-14% with shallow tillage at 2 weeks (9).

Crop rotation: Crop rotation implements various management strategies, patterns and timings to augment weed diversity. This deliberate approach helps in a diverse assemblage of weed flora over dominant species, resulting in reduced input costs. Studies show that a 9-year rotation consisting of perennial forages and

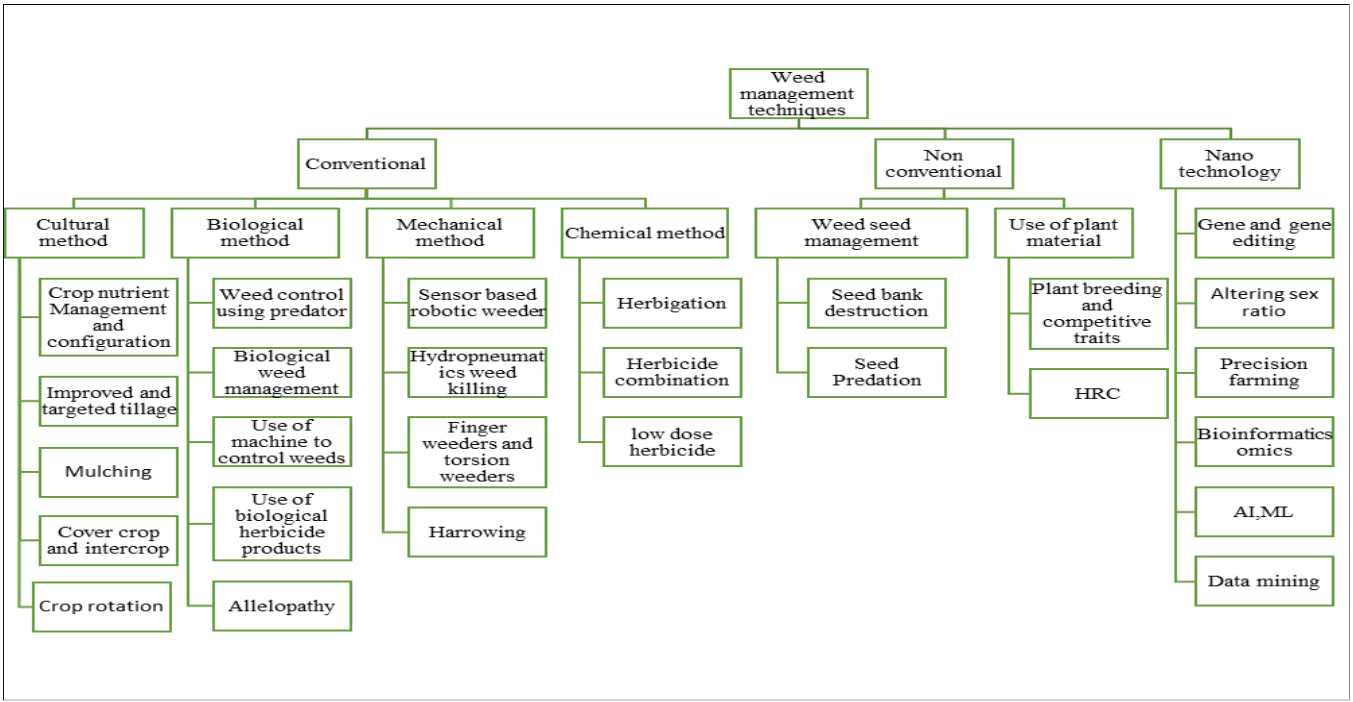

Fig. 1. Comprehensive overview of weed management techniques in agriculture.

Table 1. Common weed management techniques with targeted weeds in various cropping systems (8)

Weed management techniques	Targeted weed	Application conditions	Cropping system
Manual weeding	Broadleaf weeds, grassy weeds	Applied early in the crop growth stage, typically, within 15-25 days after sowing.	Applicable in various cropping systems, including millets, sorghum and pearl millet.
Mechanical tillage	Perennial and annual weeds	Pre-sowing or early post-emergence; best in dry soil conditions to uproot weeds.	Traditional systems; dryland farming, row crops.
Mulching	Annual broadleaf weeds, grasses	Applied after planting; organic or synthetic mulches suppress weed growth.	Suitable for horticulture and some millet-based systems.
Herbicide application	Broadleaf and grass weeds	Applied pre-emergence or post-emergence depending on weed type and herbicide.	Common in large-scale commercial systems, including rice and wheat.
Crop rotation	Mainly parasitic weeds (*Striga spp.*)	Rotational systems with non-host crops reduce weed seed banks.	Millets, cereals and pulses.
Cover cropping	Grasses, broadleaf weeds	Grown during fallow periods to smother weeds.	Millets, legumes, cereals; conservation agriculture.
Intercropping	Annual weeds, broadleaf weeds	Incorporates two or more crops to provide ground cover and reduce weed growth.	Millet-legume systems.
Biological control	Parasitic weeds, some grasses	Utilizes natural enemies like insects or fungi; climate-dependent conditions.	Less common, suitable for experimental systems.
Solarization	Annual weeds, some perennials	Applied during fallow periods; clear plastic traps heat to kill weed seeds.	Horticulture, organic farming.
Flame weeding	Broadleaf and grass weeds	Used pre-emergence or in early stages of crop growth; applied to dry conditions.	Organic systems, vegetables and some grains.
Allelopathy	Broadleaf weeds, grasses	Utilizes crops that naturally suppress weeds (e.g., sorghum, sunflower).	Sustainable agriculture, including millet systems.

annual crops will disrupt weed population growth and reduce weed density in organic systems (10). The incorporation of specific summer fodder crops before the cultivation of rice within the rice-wheat rotational system and the substitution of wheat with winter fodder crops such as oat and berseem may contribute positively to the management of winter weed populations in India (11).

Cover crop and intercrop: Cover crops compete with weeds for resources and provide a habitat for weed-eating organisms (12). The benefits of cover crops in mitigating weeds are commonly associated with their high biomass or their ability to quickly cover the soil. If the biomass and residues of these cover crops are scarce or break down rapidly, the use of herbicides may be necessary depending on the level of weed pressure. Therefore, the selection of the most suitable vegetation cover species is crucial (13).

Intercrop suppresses weed growth through competition and allelopathy allowing for more efficient use of resources. Secondly, it provides yield advantages by either using resources not accessible to weeds or converting them to harvestable material more efficiently than sole crops. Intercropping also suppresses weeds while boosting crop productivity. For instance, faba bean-barley intercropping reduced weed biomass by 76.6% and maize-legume combinations, like maize-cowpea, improved nitrogen uptake and crop competitiveness, increasing total yield by 13.6% (14-16).

Mulching: Different mulching treatments, encompassing organic and inorganic options, yielded divergent impacts on weed nitrogen content, weed frequency and weed biomass in maize cultivation (17, 18). The influence of mulch-based no-tillage on weed community dynamics and control within an organic vegetable system, indicating selective benefits or suppression of specific weed species has been discussed (19). Hydro-mulch helps in reducing perennial weeds like *Paspalum dilatatum* (87%), *Cynodon dactylon, Sorghum halepense* (around 50%), *Cyperus rotundus* (16%) in a greenhouse trial (20).

Improved and targeted tillage: Crop management practices, such as the adoption of no-till crops or the postponement of tillage, can alleviate the exposure of weed seeds to predators (such as ants and beetles) and can be integrated into weed management strategies. The retention of crop residue on the soil surface in no-till systems can suppress the emergence of weed seedlings, delay their emergence, provide the crop with a competitive advantage over weeds and reduce the necessity for control measures (21). Alternating between tillage and crop establishment systems can also mitigate anticipated shifts in weed populations. Conservation tillage, an environmentally sustainable soil management method, has been proven effective in weed control and the timing of tillage plays a crucial role in influencing weed populations, as early-season tillage has been associated with higher weed density (22). A targeted tillage method, exemplified by the 'weed chipper", has been developed for precise weed control in extensive crop production systems, boasting high efficacy in weed control while causing minimal soil disruption (23).

Crop nutrient management and row configuration: Effective crop nutrient management and row configuration play crucial roles in weed management strategies as integrating these practices can enhance crop yield while minimizing weed competition. Research indicates that manipulating fertilizer application parameters can significantly impact weed-crop interactions. Specifically, optimized fertilizer placement has been shown to reduce weed density and biomass, resulting in enhanced grain yields compared to conventional broadcast fertilization methods like in soybean (24). In a study, the application of N fertilizer changed the emergence pattern, density and competitive ability of different weeds (25). Specific row orientations, such as north-south, reduced weed density and improved crop yield in wheat, demonstrating the importance of strategic row configuration. The development of integrated weeding systems that target both inter-row and intra-row weeds has shown high efficacy in reducing weed populations, thus supporting crop health (26). While these strategies are effective, reliance on a single method may lead to weed adaptation, emphasizing the need for diverse approaches in weed management (27).

Biological weed management

All of the agroecological systems are susceptible to weed issues and it is advisable for biological control programs to consider all approaches for utilizing plant pathogens (including classical, inundative and augmentative strategies) instead of adhering to the inundative (bioherbicide) method for managing weeds in intensively cultivation as opposed to the classical approach for addressing weeds in unmanaged systems.

Weed control using microbes and viruses: Most commercially available biological weed control products are from fungi (28). For instance, BioMal, a concoction of *Colletotrichum gloeosporioides f. sp. malvae* was developed to combat round leaf mallow (*Malva pusilla*) (29). Similarly*, C. gloeosporioides f. sp. aeschynomene,* initially introduced as Collego in 1982 for control of northern joint vetch (*Aeschynomene virginica*) rebranded as LockDown in 2006 (30).

Weed control using predator: Biological weed control is accomplished in two ways: by introducing natural enemies against adventive and native weeds and by releasing or applying natural enemies at specific locations where control is required. Intraguild predation among biological-control agents can disrupt the efficacy of biological control against nematode or arthropod pests but is less common among plant pathogen and weed agents. Major examples are the control of *Parthenium* by *Zygogramma bicolorata* in India (31) and tansy ragwort (*Senecio jacobaea* L.) in New Zealand by cinnabar moth, *Tyria jacobaeae* (32) However, careful consideration must be given to potential unintended consequences and impacts on non-target species before implementing biocontrol measures.

Use of biological herbicide products: Several non-synthetic products derived from plants have been evaluated for their effectiveness in weed management. Both preemergence and postemergence applications were studied. Acetic acid (33), essential oils and pelargonic acid (34) are suitable materials for postemergence applications. Achieving selectivity with these materials will be difficult due to a generalized mode of injury.

Mechanical method to control weeds

Advancements in mechanical weed management are crucial for enhancing agricultural productivity while minimizing environmental impact. Recent innovations focus on integrating automation and precision technologies to improve efficiency and effectiveness in weed control.

Harrower & Finger weeders and Torsion weeders: Harrowing can achieve high degrees of weed control without damaging the crop which was further developed with the use of brushes and tactile hoes, which are effective in reducing the need for herbicides. If precise control over the working depth and the alignment of the harrow tines concerning the crop rows could be achieved, the process of uprooting could potentially serve as a discerning mechanism for weed control during the initial stages of crop growth (35). Finger and torsion weeder's efficacy, especially in organic or low-input farming is good compared to other weeders (36). Sensor-driven finger weeders reduce herbicide use in wide-row crops like sugar beets (37).

Hydropneumatic weed killing: Hydropneumatic systems typically involve heating air and introducing moisture, which creates a blast of hot, moist air that can penetrate and kill weeds by damaging their foliage. The use of steam, as seen in portable steam weed-killing apparatuses, allows for targeted application, minimizing collateral damage to surrounding plants. Some hydropneumatic weed killer satisfies the conditions of the technological process for eliminating weed vegetation in the stem area without the application of herbicides, while adequately achieving high technological standards. Portable steam weed-killing devices utilize concentrated steam to kill weeds. These systems can be operated by individuals and are designed for ease of use in gardens and sidewalks (38).

Full-width and inter-row cultivators: These categories encompass various mechanical devices designed to tackle specific weed problems, enhancing operational efficiency. Inter-row cultivators effectively target weeds between crop rows, significantly improving plant growth parameters and seed yield, especially when used at optimal working depth and can achieve weeding efficiencies of 60-80 %, operating at a speed of 0.7-9.7 km/h. Rolling cultivators and PTO-driven cultivators can be used for inter-row weed control (39, 40).

Automation technologies in weed management: The integration of sensors and autonomous systems has revolutionized weed management, allowing for precise targeting of weeds and reducing labor costs (41). Automated weed control is revolutionizing agricultural practices through the culmination of advanced technologies such as IoT, machine learning and robotics. These innovations enhance efficiency, reduce pesticide use and promote sustainable farming. Autonomous robots equipped with AI can detect and remove weeds, addressing the challenges of manual weed management and enhancing precision in farming (42).

Precision weed management combines mechanical, cultural and chemical methods with advanced sensing technologies, promoting sustainable practices and reducing herbicide reliance (43). Techniques like the evolving Gaussian process (E-GP) enhance the prediction of weed growth, optimizing the deployment of mechanical weeding (44). Some of the major automated technologies so far used for weed control are shown in Table 2.

Chemical weed management

To tackle these challenges like increasing resistance, a comprehensive strategy that integrates chemical and non-chemical approaches to weed management is being suggested. Some of the techniques to avoid challenges in chemical weed management.

Herbigation & herbicide mixture/combinations: Herbigation, a combination of 'herbicide' and 'irrigation' is a novel approach that combines irrigation systems with herbicide application techniques. This innovative method offers several advantages in weed control while conserving resources and promoting sustainable agricultural practices. The pre-emergence application of herbicides can be applied as habitation through the micro-sprinkler as it is recorded as comparable weed control efficiency with the conventional method of application (50).

One promising solution is the use of herbicide combinations which offer a multifaceted approach to weed control. Herbicide combinations provide distinct benefits, including broad-spectrum weed control, synergistic or additive effects, prevention of herbicide detoxification in mixtures and

Table 2. Some commercialized precision weed control technologies

Precision weed control technologies	Methodology	Example	Reference
UAV's	Combination of UAVs and GPS technologies	Utilizing centimeter-resolution RGB and CIR images captured by small UAVs for evaluating crop damage caused by dicamba application in a soybean field.	(45)
Hyperspectral imaging sensors	Hyperspectral imaging the system coupled with a micro-spray heated oil application system	FieldSpec® 4 Hi-Res from ASD Inc. (a PANalytical company).	(46)
Automatic weeders	Intra-row robotic weeder (Robovator)	Robovator developed by Garford Farm Machinery Ltd.	(47)
Precision spray systems	Autonomous robot for precision spraying	Robotized patch sprayer that achieved a 99.5% success rate in treating detected weeds.	(48)
Weed sprayers	Machine vision weed spot-sprayer	See and Spray" technology developed by John Deere.	(49)

reduction of herbicide dosage. Herbicide mixes of Fenoxaprop-p-ethyl and Imazethapyr can manage resistance in barnyard grass populations compared when used individually. Major herbicide combination used in India are Anilofos 24% + 2, 4-D 32%, Bensulfuron methyl 0.6% + Pretilachlor 6%, Fenoxaprop-p-ethyl 7.77% + Metribuzin 13.6% (51).

Low-dose herbicide: Using low doses of herbicides in weed management refers to the practice of applying herbicides at lower-than-conventional rates while still achieving effective control of weeds. Applying herbicide molecules at rates lower than the recommended dosage can effectively control weeds to satisfactory levels without compromising crop yields or exacerbating weed infestations in subsequent years. For example, atrazine was recommended to control annual weeds in maize at the rate of 2 to 4 kg ha^{-1}. Now, the same herbicide is recommended to use only at the rate of 1 to 2 kg ha^{-1}. The same efficacy is achieved by a low dose instead of a conventional dose (52). The most commonly used low-dose herbicide in rice is Bispyribac sodium 10% SC (early post-emergence) at 660 g active ingredient/ha against *Cyperus iria, Cyperus difformis, Fimbristylis miliacea, Marsilea quadrifolia, Eclipta alba, Ammannia baccifera* and *Ludwigia parviflora* and in wheat Sulfosulfuron 75% WG (post emergence) at 25 g active ingredient/ha against *Phalaris minor*, *Chenopodium album* and *Melilotus alba* (51).

Nonconventional approaches

Weed seed management

Controlling the soil seed bank to a manageable level (less than 20 million weed seeds ha^{-1}) is crucial for effective weed management, considering its composition, vertical distribution and dynamism (53). So certain methods have the potential to address the challenges of unwanted crops, crop volunteers and the emergence of herbicide resistance in weeds, which in certain systems have reached a critical threshold where the absence of sustainable practices puts productivity at risk.

Seed bank destruction: Harvest weed seed control (HWSC) is a pioneering method that was created in Australia in response to the threat of herbicide resistance in highly productive conservation cropping systems that heavily relied on chemical weed control. This encourages growers to explore alternative systems that could be integrated into cropping practices. Consequently, these systems were devised to specifically target the weed seeds that pass through the harvester during the harvesting process (54). Some of the weed seed destructor technologies are given below.

Chaff carts: It was first introduced in Australia during the 1980s and serves as an essential implement for the collection and elimination of herbicide-resistant weed seeds, including *A. fatua, L. rigidum* and *Raphanus raphanistrum* L., during the harvesting process (55).

Narrow windrow burning: This inexpensive and simple approach to the HWSC system involves the attachment of a chute to the rear of the harvester that during harvest concentrates the chaff into a narrow windrow (50-60 cm wide). Firing the entire field is not as efficacious in eliminating weed seeds as firing the chaff in the windrows (56). These windrows are later burnt when the weather is suitable to contain the fire within the windrows.

Bale direct system: The Bale direct system has successfully captured over 95% of the seeds belonging to the species *Lolium rigidum* during the harvest process. This particular approach is particularly suitable for implementation in fields where the presence of excessive straw residue hinders the subsequent planting of crops (57). Nevertheless, this approach is burdened with the drawback of affixing the chaff cart at the rear of the harvester, thereby complicating maneuverability within confined fields.

Harrington seed destructor: Weed seeds in annual grain crops pose significant challenges for farmers. In 2005, Australian grain producer Ray Harrington pioneered the use of cage mills to destroy weed seeds. Building on this innovation, researchers achieved up to 90% destruction of annual ryegrass seeds in wheat chaff during harvesting. Further modifications led to the development of the Harrington Seed Destructor (HSD), which boasts a remarkable 95% destruction rate for various weed species, including annual ryegrass, ripgut brome, wild radish and wild oat. HSD's effectiveness makes it a practical and promising solution for managing weed seed banks (58).

Chaff lining and chaff tramlining: This approach involves the collection of weed seeds and their placement in an unfavorable environment, where the physical and chemical properties of the chaff material restrict the development and emergence of the weed seeds. Increasing quantities of chaff consistently led to a decline in the emergence of rigid ryegrass seedlings through the chaff substrate (59).

Seed predation: Seed predation occurs in two forms at different times: pre-dispersal predation, which occurs while the seed is still on the weed and is not yet ripe and post-dispersal seed predation, which occurs on or in the soil surface or on another substrate after seed shedding when the seeds are consumed by seed predators.

Predispersal weed predator: Predispersal predation of seeds holds greater significance and efficacy in weed control initiatives, as opposed to post-dispersal predation, owing to the increased vulnerability of weed seeds during this phase, in contrast to their state after ripening. The dispersal predation of redroot pigweed by the species *Coleophora lineapulvella* exhibited a considerable degree of variability. However, the percentage of damaged seeds within the inflorescence that was attacked differed significantly, with values of 93% and 42% recorded respectively (60).

Post-dispersal weed predator: The small-seeded species with a diameter of less than 4mm have been affected by post-dispersal seed predation as they are primarily consumed by arthropods or molluscs (61). Scientists have demonstrated a negative correlation between the emergence rate of Italian ryegrass (*Lolium multiflorum*) seedlings and the density of crickets (62).

Usage of plant material in weed management

Plant breeding and competitive traits: Research has unequivocally demonstrated that crop competitiveness against weeds can be significantly increased through strategic plant breeding, wherein pivotal traits such as plant height, developmental rate and canopy architecture are finely tuned (63). This gives the critical importance of meticulous trait selection in plant breeding programs to ensure the preservation and enhancement of crop competitiveness.

Competitive crop cultivars have the potential to be cost-effective in integrated weed management strategies, but their competitive potential has not been a priority for breeding or farmer cultivar choice. A quick and simple protocol for assessing the competitive potential of new cultivars is needed, likely based on the combined effect of multiple traits (64).

Usage of herbicide-resistant crops

The adoption of herbicide-resistant crops has significantly transformed agronomic crop production, particularly with the widespread use of glyphosate-resistant varieties. However, the excessive reliance on glyphosate has spurred the evolution of weed resistance and emphasized the necessity for diversified weed management approaches. While the introduction of novel herbicide-resistant trait technologies, like dicamba- and 2,4-D-resistant soybeans, offers effective weed control solutions, it also escalates the risk of unintended herbicide movement and damage to susceptible plants (65). Despite the inherent challenges, the benefits of herbicide-resistant crops in revolutionizing weed management practices and enhancing both yield and profitability have been widely acknowledged (66).

Thermal, electrical, microwave and abrasion control methods

Thermal weed control, especially for annual weeds can be more effective than mechanical methods (67). Enclosed burning systems successfully suppress weeds (68) and heat-applicator machines achieve effective weed management (69). Methods like hot water, hot foam and steam show promising results in herbicide-free systems, particularly in organic farming and urban areas (70). Electrical weed control, exemplified by the Lasco LW5 lightning weeder and cryogenic systems using liquid nitrogen are effective (71). Air-propelled abrasive grits also show potential for physical weed control (72).

Allelopathy

It is a phenomenon where plants release substances inhibiting nearby plant growth and is recognized as a viable method for weed control in agricultural fields this can be harnessed through various techniques, such as intercropping, surface mulching and applying allelopathic aqueous extracts, either alone or combined with reduced herbicide use and crop rotation (73). Implementing allelopathy in weed management not only proves effective and economical but also demonstrates environmental friendliness, making it a promising alternative to chemical herbicides. Examples of allelopathy are provided in Table 3.

Novel technologies in weed management

Nanotechnology

Nanotechnology has great potential for weed management in agriculture. Nanoherbicides consist minute particles of herbicidal active ingredients and large specific surface lead increased affinity to the target. Nanoherbicides also enhanced the wettability and dispersion of agricultural formulations. Nanoemulsions, nanocapsules, nanocontainers and nanocages are some of the nanoherbicide formulations. While other nanocarriers, like rice husk nano sorbents, mesoporous silica nanoparticles and nano clay, can be used to fabricate nanoherbicides, polymers like alginate, chitosan, pectin, poly (epsilon-caprolactone), poly (methyl methacrylate) and poly (lactic-co-glycolic acid) are thought to be ideal nanocarriers for several herbicides, including paraquat, 2,4-dichlorophenoxyacetic acid, diuron, ametryn, atrazine and simazine (79). Many weed species, such as *Echinochloa crusgalli*, *Chenopodium album, Bidens pilosa, Amaranthus viridis* and *Raphanus raphanistrum*, can be effectively controlled by nano herbicides (80).

Table 3. Crop having allelopathic effect on weeds

Mulch/Crop residue/Cover crop/ Extract	Allelopathic effect	Target weed species	Reference(s)
Rice (*Oryza sativa*)	Decomposing rice straw releases allelopathic compounds such as momilactones, benzoxazinoids and phenolic acids, inhibiting the germination and growth of weeds.	*Echinochloa crusgalli, Cyperus difformis, Ludwigia spp.* etc.	(74)
Wheat (*Triticum spp.*)	Wheat straw residue releases allelopathic compounds like benzoxazine and phenolic acids, inhibiting weed germination and growth.	*Avena fatua, Setaria viridis, Amaranthus retroflexus.*	(75)
Sorghum (*Sorghum bicolor*)	Sorghum residue contains allelopathic compounds like sorgoleone, which inhibit the germination and growth of certain weed species.	*Palmer sp., Cyperus sp., Digitaria sanguinalis.*	(76)
Oat (*Avena sativa*)	Decomposing oat residues releases allelochemicals that suppress the growth of certain weed species.	*Chenopodium album, Amaranthus retroflexus, Setaria pumila.*	(77)
Buckwheat (*Fagopyrum esculentum*)	Allelopathic compounds from buckwheat residues inhibit the germination and growth of weeds.	*Setaria italica, Abutilon theophrasti, Echinochloa crus-galli.*	(78)

Researchers have developed a polymer that responds to light to regulate the release of herbicides (79). While also engineering a system that reacts to biological stimuli using nanoparticles made of mesoporous organosilica (81). These investigations emphasize the significance of delivering herbicides in a manner that is both environmentally safe and specific to the intended target. Collectively, these findings underscore the potential of employing smart delivery mechanisms at the nanoscale to augment the efficacy and safety of herbicides. The use of atrazine herbicide causes problems to the environment due to its high residual activity. A recent study from Tamil Nadu Agricultural University in India offers hope for removing atrazine residue from soil quickly by applying silver nanoparticles stabilized with carboxy methyl cellulose (CMC) nanoparticles can degrade 88% of atrazine residue in a controlled environment (82).

RNA interference

RNA interference (RNAi) is a gene silencing mechanism caused by the introduction of dsRNA, resulting in mRNA degradation and has potential implications in developmental biology. The discovery of RNAi is a promising frontier in plant genomics and crop improvement, as well as reducing allergenicity by silencing plant allergens. RNAi is an innovative technology for managing resistant weeds, but commercialization is still distant. The technology 'BioDirect' uses synthetic cDNA to inhibit weed growth by restoring glyphosate efficiency in resistant weeds through EPSPS gene amplification which is still in the process of commercializing (83).

Gene and genome editing

Genome editing is revolutionizing weed management by providing innovative solutions to combat herbicide-resistant weed populations and enhance crop resilience. This technology, particularly through CRISPR/Cas9, allows for precise modifications in plant genomes, facilitating the development of herbicide-resistant crops that can effectively manage weed competition while minimizing chemical use (84). An important step in this approach has been the creation of the International Weed Genomics Consortium (IWGC), which offers a forum for international collaboration and communication in weed genomics research. Transgenes have the potential to reduce insecticide and fungicide use, but not much has been done to reduce herbicide use. Recent strategies aim to change this, such as improving weed-specific biocontrol agents, enhancing crop competition or allelopathic traits and producing self-destructing cover crops. Altering the herbicide-target gene can confer herbicide resistance. For example, deletion of PPO Gly210 in weedy *Amaranthus* makes it resistant to glyphosate (85).

Herbicide-resistant crops have been developed because of new technology like CRISPR/Cas9 technology, which has demonstrated significant promise in weed management. Studies are being carried out in developing herbicide-resistant crops by the CRISPR/Cas9-mediated gene editing technology, targeting endogenous genes such as acetolactate synthase (*ALS*), 5-enolpyruvylshikimate-3-phosphate synthase (*EPSPS*), cellulose synthase A catalytic subunit 3 (*CESA3*) and splicing factor 3B subunit 1 (*SF3B1*) (86).

Weed modelling

Weed modelling plays a crucial role in effective weed management by simulating crop-weed interactions and predicting yield losses. Various models have been developed to understand these dynamics, each with unique strengths and applications. Models like (RIM and ALMANAC) that amalgamate existing quantitative knowledge are pivotal in this endeavor, as they facilitate the design of preventive measures, formulation of both short-term and long-term weed management strategies, assist in decision-making regarding the timing, location and method of weed control and uncover new avenues for effective weed management (87).

Eco-physiological simulation models, which emulate the growth and production of various species within mixed environments based on plant eco-physiological processes and responses to environmental stimuli, serve as invaluable tools for enhancing comprehension of crop-weed systems. They not only aid in constructing simple predictive models to estimate yield loss and establish threshold levels but also contribute to the development of competitive crop varieties (88). Although mathematical models have been very helpful, more has to be done to incorporate different features of weed control, like weed dispersal and multispecies assemblages, into these models. Although weed population can be better understood and predicted with the help of simulation models, there are still gaps in our knowledge that need to be filled (89).

Altering sex ratio and phenological changes for reducing weed fitness

Environmental stressors and herbicides have been identified as influential factors in altering the sex ratio of *Amaranthus palmeri* populations, potentially leading to reduced seed production (90). Given that high seed production can worsen herbicide resistance issues, it is very important to employ integrated weed control methods that include both herbicidal and cultural practices for managing *Amaranthus spp.* in corn fields. The ability to manipulate the sex ratio of *Amaranthus spp.* Weeds through environmental stressors and herbicides present a promising avenue in weed management strategies, offering a nuanced approach to mitigate herbicide resistance and enhancing overall control efforts.

Phenological isolation represents a potent mechanism for reducing seed output in dioecious weed populations and holds promise for ecological weed management strategies. By exploiting differences in the timing of reproductive phases between male and female plants, phenological isolation effectively minimizes opportunities for cross-pollination, thus diminishing overall seed production (91). This approach aligns with the principles of sustainable agriculture and biodiversity conservation.

AI, big data and machine learning

Scientists highlight the application of supervised learning methods, particularly neural networks in the identification of undesirable plants (92). It revealed the necessity of AI-driven tools and methodologies in countering herbicide-resistant plants, particularly in the realms of remote sensing, robotics and spectral analysis (93). These investigations collectively propose that AI and machine learning possess the potential to considerably enhance practices related to the management of unwanted vegetation. Some are achieving high F1 scores using deep-learning image processing for weed detection (94, 95).

Scientists demonstrated the effectiveness of rotary-wing unmanned air vehicles (RUAVs) in treating aquatic weeds, highlighting the flexibility and cost-effectiveness of small UAVs (96). UAV will ensure early site-specific weed management through high-resolution imagery. These studies suggest unmanned vehicles offer cost-effective and efficient weed management solutions (97). Hyper-spectral imaging has shown promise in weed management, detecting weed infestations and nitrogen status (98). However, distinguishing combined weed and nitrogen effects is challenging. Hyperspectral remote sensing, especially with UAVs, aids weed detection in rice fields (99), highlighting its potential in weed management.

Bioinformatics and other omics technologies

The utilization of omics technologies in weed management holds significant promise for transforming the field, especially concerning herbicide-resistant weed populations. These advanced methodologies encompassing genomics, transcriptomics and metabolomics offer an enhanced comprehension of weedy characteristics and their underlying molecular mechanisms, thus facilitating more efficacious management approaches (100). Essentials in this approach are bioinformatics resources, such as gene identification tools and protein domain databases, which play a pivotal role in identifying potential herbicide targets and unravelling plant-pathogen interactions (101). Looking forward, the way of weed management is likely to incorporate a blend of emerging technologies, including natural product exploration, genetic manipulation and machine vision, to effectively tackle the complexities of herbicide resistance and optimize food production (102).

Data mining

Data mining, a major aspect of modern agricultural innovation is revolutionizing weed management practices by harnessing the power of data to optimize decision-making, enhance efficiency and mitigate the impact of weeds on crop yields. Recent studies highlight the importance of labelled weed databases for training AI models, which can achieve detection accuracies exceeding 92% in controlled conditions, although performance may drop in varying field conditions (103). The creation of comprehensive weed datasets, such as the Moving Fields Weed Dataset, includes over 94,000 images of 28 weed species, enabling advanced machine vision applications for accurate species classification (104). Decision support systems for weed control either focus on expert advice (105) or model-based support for arable farmers was reported (106).

A sustainable approach in weed management

Agroecological weed management (AWM) emphasizes sustainable, ecological approaches to controlling weeds while enhancing biodiversity. It reduces reliance on synthetic herbicides by promoting non-chemical strategies, such as increasing crop competition through cover crops, intercropping, diverse crop rotations and altered sowing schedules to disrupt weed life cycles (107). AWM also focuses on landscape-scale interventions to improve biodiversity and ecosystem functionality. While AWM offers ecological benefits, its implementation faces challenges in balancing sustainability with economic viability. Compared to Integrated Weed Management (IWM), which combines chemical, mechanical and biological methods for economic efficiency, AWM aims to restore biodiversity and minimize chemical inputs (108). IWM's focus on immediate control may reduce biodiversity, whereas AWM promotes long-term ecological health (109). Both systems address herbicide resistance and environmental degradation, with AWM also advancing sustainable agriculture by enhancing farmers' autonomy and resilience to market fluctuations, contributing to food security and climate resilience (Fig. 2).

Furthermore, the adoption of agroecological weed management aligns with the principles of sustainable agriculture, addressing broader societal concerns such as food security, rural livelihoods and climate change resilience. By reducing dependence on chemical inputs, agroecological systems enhance farmers' autonomy and resilience to market fluctuations, ultimately contributing to more equitable and resilient food systems. Multidisciplinary teams of scientists, engineers, economists, sociologists, educators, farmers, land managers, business people, policy makers and others willing to concentrate on weeds within entire farming systems and land management units will be needed to implement new weed management strategies (110).

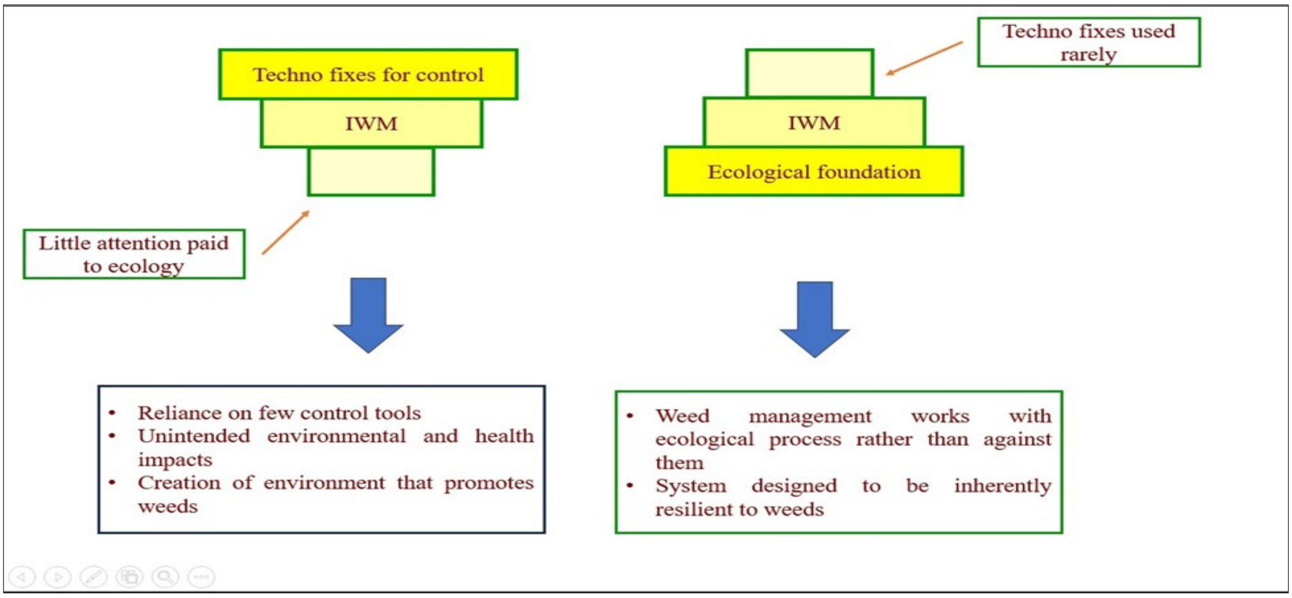

Fig. 2. Integrated weed management and agroecological weed management.

Conclusion

Traditional weed management predominantly utilizes herbicides, mechanical cultivation and manual removal, which are labour-intensive, economically burdensome and detrimental to environmental and human health. Transitioning to agroecological practices is imperative due to the deleterious effects of synthetic herbicides, including soil degradation, water contamination and biodiversity loss. The potential benefits of improving weed management with strategies based on ecological and evolutionary principles include better long-term protection of food production capacity and farm profitability, less damage to non-target species, water and other resources, greater integrity of plant and animal communities in non-agricultural areas and maintenance of weed susceptibility to control practices (i.e., herbicide resistance prevention). Achieving these benefits will require multidisciplinary teams comprised of scientists, engineers, economists, sociologists, educators, farmers, land managers, industry personnel and others willing to focus on weeds within whole farming systems and land management units. Adopting ecological principles in weed management promotes resilient agroecosystems, conferring benefits to both agricultural producers and the environment, thereby ensuring a sustainable future for agriculture.

Authors' contributions

AMV executed the experiment and collected the data. RB conceptualised and supervised the experiment and analysed the data. AMV prepared the manuscript. CH participated in its design and coordination. RK, PB, RJ gave guidance. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used assistance of generative AI tools such as Chatgpt to aid in language editing and locating readability. After using this service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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